Space Communications Technologies for Interstellar Missions

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Abstract

This paper will examine candidate communications architectures for potential interstellar missions in an effort to determine feasibility for such links and to identify likely technology advances that will be needed to support such endeavors. Examination of this challenging and futuristic communications problem may serve to guide the direction and advancement of space telecommunications technologies useful for other nearer-term applications.

Introduction

I-he paper will begin with a survey of proposed telecommunications architectures for previously studied interstellar mission designs. These include the Interstellar Precursor and Thousand Astronomical Unit (TAU) missions studied at the Jet Propulsion Laboratory in the 1970s and 1980s respectively, as well as the Daedalus Project studied by the British Interplanetary Society in the late 1970s. The feasibility of these architectures will be assessed against recent programmatic trends, such as mission cost reduction, and technological trends, such as flight system miniaturization. For a representative mission designed in the current era, performance of radio and optical frequency links will be assessed. implications for the design of flight and ground telecommunications systems will be described. The capabilities and deficiencies of current technologies will be presented and the potential of foreseeable technology advances will be highlighted.

Interstellar Communications Architecture Trends

Over the past 15 to 20 years, there have been a number of credible studies of missions to targets beyond the solar system. Two missions in this category, studied at the Jet Propulsion Laboratory in 1977 and 1987 respectively, are the Interstellar Precursor Mission,[1] and the Thousand Astronomical Unit (TAU) Mission.[2] The Interstellar Precursor Mission was primarily intended to explore the characteristics of the heliopause, the interstellar medium, stellar distances by parallax measurement, low energy cosmic rays, interplanetary gas distribution and mass of the solar system. A secondary objective was investigation of the Pluto system. Non-stellar targets were selected due to the perceived lack of capability to launch a spacecraft to another star in a reasonable length of time. The intended launch date was 2000, with a nominal duration of 20 years, and an extended duration out to 50 years. A heliocentric hyperbolic escape velocity of 50-100 km/s was sought in order to achieve distances of 500- 100(1 AU from the Sun. A nuclear electric propulsion system was selected to achieve these velocities. Characteristics of the radio-frequency telecommunications system for both spacecraft and ground elements are shown in Table 1.

I-he TAU mission was, in some ways, a modernized version of the Interstellar Precursor. Targeted to the same distance from the Sun, it's primary objective was measurement of the galactic scale through stellar parallax astrometry; secondary objectives included astronomy, astrophysics, cosmology and space plasma physics. TAU had the benefit of an additional ten years of technology development This allowed it to baseline a more advanced telecommunications architecture, specifically utilization of optical frequencies. Relevant communications parameters are given in the table.

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Table 1. Telecommunications Systems for Early Interstellar Mission Designs

Parameter	Interstellar Precursor	TAU Mission	Daedalus Project
Range (at design point)	1000 AU	1000 AU	7 LY
XMIT Antenna Diameter	High-gain 15 m	1 m telescope	High-gain 5 m
Beamwidth at $^1/_2$-Power	0.16 deg	0.92 μrad	1.15 deg
Gain	62 dB	134 dB	45 dB
Wavelength	3.55 cm	0.532 μm	11.4 cm
Frequency	8.450 GHz (X-band)	560000 GHz (Optical)	2.60 GHz (S-band)
XMIT Output Power	40 W	10 W	1 MW Klystron
Channel Coding	Convolutional (k=7; r=$^1/_3$)	Reed Solomon 10-bit | 10-bit	N/A
Bit Error Rate	10^{-4}	10^{-6} | 10^{-6}	N/A
E_b/N_0	3.2 dB	N/A | N/A	N/A
Tracking Loop Bandwidth	1 Hz	N/A | N/A	N/A
Transmission Bandwidth	300 Hz	Large | Large	432 kHz
RCV Antenna	100m	10 m telescope	1000 64m (Cyclops array)
Data Rate	100 bps	20 kbps 0 kb	864 kbps
Downlink Time	Continuous	Continuous	1.5 days

In contrast to the two missions studied at JPL, the Daedalus Project, proposed as a feasibility study by the British Interplanetary Society in 1978, was a true mission to another star, namely Barnard's Star, at a nominal range of over 6 light-years (LY).[3] The proposed spacecraft was to be propelled by a relativistic-electron induced pulsed thermonuclear fusion engine to a final velocity of 12% of the speed of light (0.12c), and then coast to its destination in about 50 years flight time. Although this mission was very forward-looking, its designers chose to constrain themselves to reasonable extrapolations of current technology. The published characteristics of its telecommunications system, again at radio frequencies for both spacecraft and ground elements, are also shown in the table.

In comparing the two radio-frequency (RF) designs, the table shows that the Daedalus Project requires a much more capable telecommunications architecture than does the Interstellar Precursor. This is primarily due to the extreme differences in range (factor of 1700) and data rate (factor of 8600). However, in some ways the Interstellar Precursor uses more advanced technology than does the Daedalus vehicle, e.g., a higher frequency band and a more sophisticated form of channel coding. The way in which the Daedalus designers enabled the downlink of their acquired data was essentially to attack the problem with a great deal of capacity, both on the vehicle and on the ground. 1 MW of RF output from a spacecraft transmitter is a tremendous amount of power, although it does make sense in the context of the Daedalus vehicle design. Since that vehicle was intended to be powered and propelled by pulsed fusion technology, it is easy to see that this level of power for the telecommunications system would not be unreasonable. Further, the morphology of the vehicle's second stage, which carried its payload (66,000 kg and 110 m long), would provide adequate capability to dispel waste heat. On the ground side of the link, the plan was to use the F'reject Cyclops array of 1000 64m diameter antennas.[4] This array had previously been proposed as part of a Communications with Extra-Terrestrial Intelligence (CETI) initiative, As it was anticipated to exist in any case, the intent was to leverage that development for the short space of time required for the downlink of Project Daedalus data. However, as is the case with many such grandiose proposals from that era, the Project Cyclops array never materialized.

Since the late 1970s, there have Linen a number of programmatic and technological developments that may now make it timely to reconsider the kinds of telecommunications systems that might reasonably be applied to interstellar missions. The programmatic developments are most succinctly summed up in the now well-recognized phrase "faster, better, cheaper." The current trend is to see how much can be done with how little. Specifically in the area of interstellar studies, researchers are discussing spacecraft whose mass is on the order of 100 g to 1 kg. Further, cost reductions will be expected for ground operations. Against this backdrop it is unlikely that anything like the Cyclops array will be constructed any time soon. However, not all the developments arc bleak. New technology advances enable the design of communications links at higher microwave, anti even optical, frequencies. This, in turn, enables greater directivity, higher gain anti a resulting improvement in link margin. Other technologies that have advanced substantially since the early interstellar mission studies arc channel coding and source coding, i.e., data compression.

With these developments in mind, we can now examine some updated architectural concepts that can be applied to the problem of establishing a communications link across interstellar distances. A representative mission is likely to traverse distances on the order of 250,000 Astronomical Units (~ 4 LY) with a final speed on the order of 10% of the speed of light (0.1 0c). In this case, the spacecraft would take about 50 years to reach its target. Successful execution of such a mission has a number of driving requirements. First, critical events must be carried out. For 4 LY distances the Earth-to-space command communications link becomes impractical due to the enormous signal propagation delays. Thus the use of on-board programmed sequences, i.e., full autonomy, will be required. Second, the spacecraft must have the life expectancy to be able to reliably operate for several decades. Finally, scientific data must be returned to Earth. In the analyses that follow, it will be assumed that the first two requirements are able to be met. This paper will then only examine the capability to downlink science data back to Earth, which is expected to be the main driver of telecommunications system design.

Radio Frequency Communications Link Architecture

Feasibility of communications with a spacecraft at radio frequencies over distances of 4 LY has been examined. Analyses were performed to determine spacecraft and ground equipment requirements to establish a communications link which could receive telemetry data with modest performance margins. Tradeoffs between the various transmission parameters such as ground and spacecraft antenna aperture, spacecraft transmit power, data rates, operating frequencies, and link margins were used to show the degree of performance under a variety of possibilities,

Transmission Frequency Optimization

Proper choice of the down-link radio frequency is a crucial factor for optimizing link margins. Considering the advantages and disadvantages of using one frequency over another, the net effects should result in overall improvements to the link margin. In this hypothetical design, an operating frequency in the region of 90 GHz was found to be the most favorable. Signals with frequencies between 50 GHz and 75 GHz are subjected to high attenuation due to the oxygen absorption in the troposphere. Alternately, signals with frequencies above 100 GHz become severely attenuated by the water vapor content in the troposphere. The frequency of the received signal will also be noticeably Doppler shifted downwards due to the spacecraft's radial velocity. This can amount to several GHz. This has two effects: first, it can shift the received frequency into a band where atmospheric attenuation is severe, and; second, it results in an increase in space losses from the lowered effective frequency. However, it is relatively easy to predict and compensate for these effects.

Table 2 illustrates three candidate design points for an RF telecommunications architecture, all of which utilize the 90 GHz frequency band. The first design, which assumes a spacecraft with a 1 MW transmitter and an antenna diameter of 14 m, yields data rates of 7.5 bps, at a single 70 m antenna ground station. The data link margin for the selection of these transmission parameters is expected to be about 4 dB to attain a bit-error-rate of 10-s. A coding scheme using Reed-Solomon (255,223) concatenated with an inner convolutional code (k= 15 and rate $^1/_6$) was assumed in the calculation. The other two designs utilize more modest, though still high, power levels. To make up for the reduced power, they rely on larger apertures both on the spacecraft and on the ground. In fact, these designs obtain the necessary ground aperture by means of large antenna arrays on Earth.

Table 2. Representative Radio Frequency Interstellar Link Parameters

Frequency (GHz)	Number of 70 m Ground Antennas	Spacecraft Antenna Diameter (m)	Spacecraft Power (kW)	Data Rate (bps)	Bit Error Rate	Link Margin (dB)
90	1	14	1000	7.5	10^{-5}	4
90	20	25	100	30	10^{-5}	4
90	100	30	10	60	10^{-5}	—4

High Powered Spacecraft Transmitter

The assumption was made that a transmitter capable of delivering 1 MW average power to the spacecraft antenna could be developed for this interstellar mission. Present state-of -the-art power transmitters are of the gyrotron class. High power gyrotrons operating at 140 GHz with 1 MW average output power are presently under development for plasma heating purposes.[5] Development of these oscillators into a power amplifier or gyroklystron is now realizable; however, their large cryogenic magnets would add significant mass to the spacecraft payload. Other problems associated with the use of such a high power device will be that of power supply and cooling. H the power amplifier is assumed to have 40 percent efficiency, then the on-board power source must be capable of providing at least 2.5 MW of power. 1.5 MW of the gyroklystron power would be expended as heat, giving rise to an additional mass requirement to dissipate the excess heat.

In the event that 1 MW class RF power amplifiers remain insufficiently mature or cannot be accommodated on interstellar spacecraft, the deficit in transmission power will have to be compensated with increases in spacecraft and ground antenna aperture.

Spacecraft and Ground Antennas

As determined by their aperture size, the gains and directivity of both the spacecraft and ground antennas are major elements in the space communications link. An increase in the link margin can be attained by a corresponding increase in either the spacecraft or ground antenna aperture. Due to the mass restrictions of the spacecraft, it becomes more feasible, at some point, to increase the ground station aperture. The maximum size of spacecraft antenna is determined by the state-of-the-art hardware and deployment technology, whereas the ground station antenna size is limited only by its complexity and cost. Additionally, because of their *very* narrow beamwidth, the pointing accuracy for antennas with large dimensions becomes increasingly critical at the higher frequencies, The half-power beamwidth of a 70 m antenna would be on the order of 0.003 deg at 90 GHz. Some additional link margin will be necessary to account for the spacecraft and ground terminal antenna pointing errors caused by atmospheric refraction, spacecraft motion, and the control limitations of the antenna pointing mechanisms.

Requirements for large antenna aperture may range from the use of already existing antenna networks to the construction of several new structures, which would add significant costs to the mission. The ground station antenna aperture can be augmented using an array of antennas which phase-combine the received signals, effectively increasing the received power in proportion to the number of antennas in the array. These can be either clustered together or at other remote locations. Since the 70 m antenna is the largest NASA Deep Space Network (DSN) antenna in use today, it was given in the link analysis as the basic unit of antenna aperture on the ground. The tradeoff relationship among the key communications design parameters, including spacecraft transmitter power, spacecraft antenna aperture, operating frequency, ground antenna aperture and resulting data rates is shown in Fig. 1.

Ground Systems

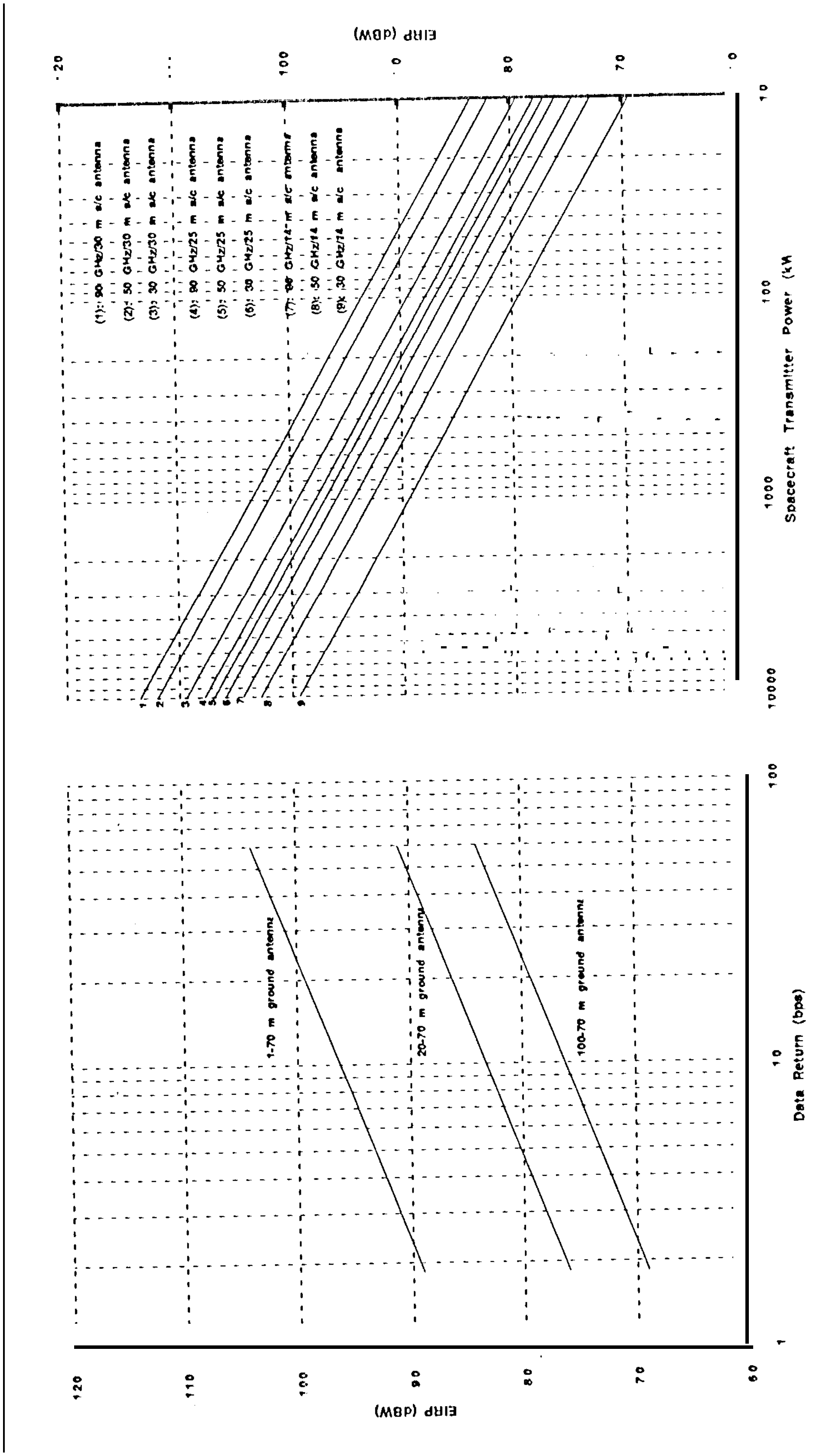
Unlike spacecraft equipment technology, ground station equipment will continue to evolve during the cruise phase of the interstellar mission. Improvements in digital receiving systems are expected to continue with the development of more sensitive receiver front ends. High Electron Mobile Transistor (HEMT) low noise amplifiers and Superconductor- insulator-Superconductor (SIS) mixers have been greatly improved for operation at the higher frequency bands. Cooled HEMT amplifiers and SIS mixers in the 90 GHz range have noise temperatures *on* the order of 100 K and 75 K, respectively. The noise figure of the receiver front end amplifiers will continue to undergo improvements, bounded by the photon noise temperature quantum limit (e.g. 5 K at 90 GHz).

Receiver sensitivities have increased dramatically with the development of digital receivers. Digitized IF stages in the receiver far exceed the sensitivity and stability capabilities of the analog receivers. Phase-locked loop circuits can now track signals with a loop bandwidth of a fraction of a Hz. Such a narrow bandwidth is preferable when the tracking loop compensates for fluctuations and instabilities in the signal's frequency and phase.

Inflatable Deployable Antennas

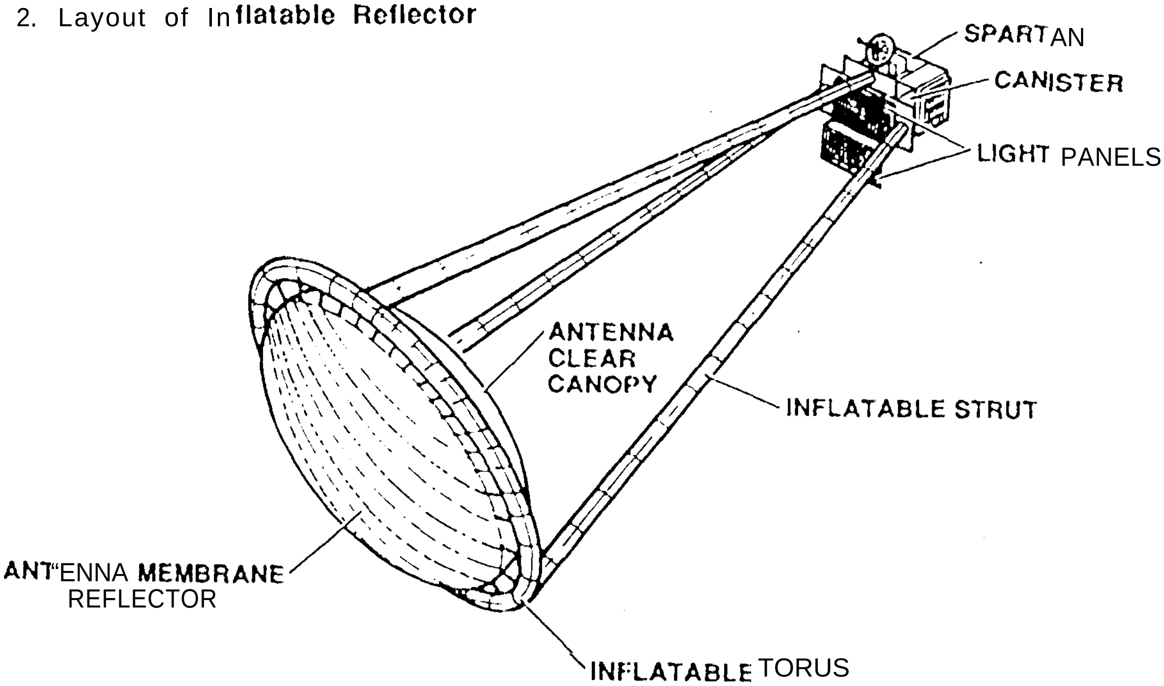
Large space-deployable antennas have problems resulting from high hardware costs, concern about mechanical deployment reliability, and weight. For example, a 15 to 30 meter diameter mechanically deployable space antenna structure would cost on the order of several hundred million dollars. Furthermore, mechanical concepts in this size range, have not actually demonstrated high deployment reliability.[6]

Figure 1. Radio Frequency Performance Trade Space for 4 LY Distance



A new concept has resulted from recent technology developments in the area of large *inflatable* deployable space structures, having low cost, light weight, and high deployment reliability. Fig. 2 shows the mechanical layout of the L'Garde, Inc. offset, parabolic reflector antenna. Deployment is accomplished by the insertion of inflation gas sequentially to the stowed struts, torus, and reflector/canopy, respectively. The L'Garde inflatable antenna has been selected by NASA for an In-Space Technology Experiments Program (IN-STEP) mission. Currently it is expected to launch into Earth orbit a 14 m parabolic inflatable antenna in May of 1996. Antennas operating in the region of 94 GHz are now being developed for applications in active microwave sensing.

Figure 2. Layout of Inflatable Reflector



The long term design goal of the reflector structure surface precision must be at least 0.2 mm in order to achieve the performance shown in the link analyses. At frequencies in the 90 GHz region, the reflector surface tolerance will have a substantial effect on the antenna efficiency. Presently, the achievable limit of the reflector's surface tolerance is 1 mm RMS; however, efforts continue towards the achievement of higher precision and reliability after deployment. Research is ongoing to develop more efficient methods of extending the antenna structural components from the stowed position to the fully opened position. Also, reflector configurations and surface materials are being sought with a memory for adjusting the metallic reflector surfaces, resulting in a higher level of precision.

Geostationary Satellite and Lunar Based Relay Systems

As the radio signal is transmitted from the spacecraft to Earth it propagates through several layers of the ionosphere and troposphere, undergoing impairments to its frequency, phase, and amplitude. At frequencies near 90 GHz, atmospheric attenuation due to oxygen absorption and water vapor can appreciably degrade the link performance, especially at low antenna elevation angles. An additional 3 dB of link margin would be required to compensate for these propagation impairments for 90 percent of the time.[7]

The problem can be alleviated with the deployment of satellite relay stations at the geostationary orbit by intercepting the signal and then retransmitting it to Earth at a higher power level. A system of relay satellites would increase link availability and substantially reduce signal degradation due to atmospheric attenuation. However, the free space losses (spreading losses) account for most of the signal attenuation, and the economic feasibility of using satellite relay stations to marginally improve the link performance would be questionable.

Similar to the the geostationary satellite relay, a lunar-based relay system can also improve the link performance. The lack of atmosphere at the Moon offers an ideal environment for the signal reception. An array of antennas would further enhance the signal level, and a strategic distribution of antennas on the lunar surface would provide continuous coverage of the received telemetry data.

Optical Frequency Communications Link Architecture

Past Mission Studies

Optical communications utilizes very short (micron-sized) electromagnetic wavelengths and hence has the potential of greatly improving communications capabilities from very long distances. This technology has been considered in the past for applications in long-range (extra-solar system distance) missions. Early mission studies[1,3] led to the conclusion that RF technology was more advantageous and hence baselined the more familiar technology. However, these studies reached conclusions that are no longer held as correct for reasons of either lack of understanding of the properties of optical communications, or a lack of confidence in the projections made with the technology.

For example, the Interstellar Precursor study concluded that an optical link was far inferior to an X-band RF link because a) performance predictions were based on assumed but inaccurate scaling laws, and b) it was believed that optical beams were too narrow to be reliably pointed since the pointing accuracy requirement was 3 orders-of-magnitude smaller than the state-of-the-art microwave systems.

The Project Daedalus study concluded that "a radio link is far more efficient than a laser system for long distance communication due to the much lower background photon noise." I-his is despite the fact that the favored RF solution required a 5 m antenna with a 1 MW transmitter on the spacecraft, and a "Cyclops-sized" receiver array on the Earth. I-he study did not appreciate the actual noise statistics of the channel, or the degree to which background light could be filtered out. Actually this study did recommend an optical link for the shorter range "boost" phase, but only because it was felt that RF could not penetrate effectively through the plasma thruster plume.

1 hese early studies were based on the understanding of optical technology at the time the studies were performed.

Recent Technology Developments

Fortunately much progress has been made since the 1970's in the technological maturity of optical components and in the understanding of the properties and benefits of optical communications systems. We present here some of those major advances. A more thorough treatment of these technologies can be found in Ref. 8.

Lasers: In the 1970's, lasers were either gas lasers that operated at only a few percent efficiency, or were flashlarnp-purnped solid state lasers that were even less efficient. 1 oday, there are semiconductor laser transmitters that produce over 1 W of output power in a single spatial mode beam pattern that are 40% efficient and both the power levels and efficiencies are still rising. Solid-state lasers have also become much more efficient since diode lasers can be used as pumping sources rather than flashlamps. Diode laser pumps are both highly efficient at generating the pump energy and the output energy can be spectrally matched to, and concentrated in, the absorption spectrum of the lasing material. Laser power levels have been consistently doubling every year and the trend shows no slowing down.

Detectors: In the 1970's, most laser communications studies assumed the use of CO_2 lasers operating at the 10.6 micron wavelength. Detectors for such signals had to be cryogenically cooled to reduce thermal noise and required a stabilized mixing reference laser for heterodyning purposes. Presently, almost all practical lasercom designs utilize wavelengths in the visible or infrared, and use direct detection of the received photon energy. These systems have become practical because of great progress in efficient (direct) photodetectors. Currently, detectors with 60% or more quantum efficiency and with internal photomultiplicative gain are available. Additionally, arrays of efficient photodetectors are available which greatly simplify the acquisition, pointing and tracking functions required for beam control.

Pointing/Tracking: Most early studies of optical links were performed by researchers who were RF communications specialists. In RF communications, the more narrow the transmitted beam (due to smaller wavelengths or larger apertures), the more accurately the RF antenna had to be pointed. 1 his paradigm carried over into the optical studies where it was felt that the extremely small wavelengths (and hence extremely narrow beamwidths) just simply could not be pointed adequately well. t lowever, optical technologists have solved this problem over and over again. All optical communications systems assume from the beginning that a) there is some form of beacon signal emanating from the intended receiving station (often times this beacon signal is a solar-illuminated planet, or the Sun itself), and that b) subsequent beacon tracking and downlink beam pointing will be accomplished with a small steerable optical *element* in the optical train, rather than pointing of the telescope aperture itself. All that is required of the telescope (primary aperture) is that it be pointed such that the beacon signal is in the telescope focal plane's field-of-view. This field-of-view is comparable to the deadband limit-cycles of present-day spacecraft attitude control systems. Acquisition of these uplink beacon signals is greatly enhanced by the availability of state-of-the-art detector arrays (as described above). Beam tracking and pointing at minute fractions of a laser beamwidth have been demonstrated many times, both in laboratory set-ups and in flight-qualified systems.

Narrowband Optical Filters: Another common misconception is that laser communications, while perhaps possible in the night, certainly will not work in the daytime. This is absolutely not true. In the first place, most people view "daylight" through the filters in their eyes. The human eye responds to a band of wavelengths about 4000 Angstroms wide. However, laser signals are inherently spectrally narrow; often times more narrow than .01 Angstroms. Today, very simple optical interference filters with high (e.g. 80%) throughput can be purchased. Additionally, even narrower filters (down to the 0.01 Angstrom level) are being fabricated based on atomic resonance line transitions. Additionally, it is also possible to select certain wavelengths, and to create matching filters, that operate at certain wavelengths called Fraunhofer lines. Fraunhofer lines are bands of the solar spectrum where the Sun's photosphere strongly absorbs solar energy. Such lines are dark lines in the solar spectrum.

Visibility Statistics/Diversity Reception: Much has also been learned about cloud statistics and the degree to which spatial diversity reception can mitigate the effects of cloud outages. Extensive satellite-acquired data bases, as well as records kept for decades at astronomical observatories have shown that typically good viewing sites have 60-70% cloud-free availability. These gross statistics are being further validated and refined by a program at JPL called the Autonomous Visibility Monitoring (AVM) program, The AVM program has deployed a set of three completely autonomous observatories that track stars and measure the atmospheric transmittance. AVM sites have been established at JPL (Pasadena, CA), Table Mountain Facility (Wrightwood, CA), and at Mt. Lemmon (near Tucson, Arizona). The sites are collecting a substantial data base of detailed outage statistics, both for individual sites, as well as for a spatially diversified reception network. With a set of three receiving stations spaced around the southwestern US and located in independent weather cells (a few hundred km apart), the joint availability is approximately 97%.

Signal Design and System Performance: Finally, much progress has been made in the general understanding of optical communications system performance characteristics, and in the design of optical signaling formats that are *very* energy-efficient. For example, it has been found that higher-order pulse position modulation (PPM) signaling schemes are very power efficient, in the same way that orthogonal signaling is an efficient method of using the RF channel. Furthermore, the granularity of optical energy that comes from the larger energy of an optical photon has, in the past, been treated as an insurmountable optical noise. Current systems designs have learned to correctly model this granularity as a statistical distribution of the "signal" level, rather than as a (Central-Limit-Theorem-averaged) noise. This improvement in understanding has resulted in much more efficient system designs.

Recent Design Examples

Recently there have been a number of studies of long-distance mission applications that have taken much of these technology advances into account. For the Thousand Astronomical Unit (TAU) mission, data would be sent back via laser to the Earth. Table 1, shown earlier, summarized this link design, which utilized a 10 W laser and 1 m diameter telescope on the distant spacecraft. A 10 m diameter Earth-orbiting photon bucket receiving aperture was assumed, A photon bucket is a telescope which does not require as precise a surface tolerance as a diffraction-limited imaging telescope. A data transfer efficiency of 1 bit/photon was assumed. This is not unreasonable since in 1980, JPL demonstrated a direct detection optical link that could transfer over 2.5 bits of information per detected photon.[9] The link could deliver 20 kbps of data from a range of 1000 AU. Also, as the spacecraft traveled out to that distance it could be performing scientific investigations along the way. At shorter ranges (e.g., 100 AU) the link could support correspondingly higher data rates (2 Mbps in this case).

A second recent study was performed two years ago for the Pluto Flyby mission.[10] This mission was severely constrained in mass, power consumption and size. The baseline design was to use X-band communications with a 1.47 m diameter antenna and a 3.0 W transmitter. This link could support only 40 bps into a 34 m ground antenna. Contrast this with an optical link using only a 0.5 W laser and a 10 cm telescope (about the diameter of the RF antenna subreflector). The data rate into a 10 m ground-based photon bucket was 2000 bps; a factor of 50 times more than the X-band. The mass of the optical terminal was only about 1/3 that of the RF system, and the electrical power was only slightly more (and could have been reduced if the data rate advantage was reduced). Table 3 shows a comparison of the optical design and the baselined X-band link.

Table 3. Pluto Fast Flyby Mission Link Comparison

Parameter	Optical Link	RF (X-Band) Link
Range (at design point)	31 AU	31 AU
XMIT Antenna Diameter	10 cm	147 cm
XMIT Output Power	0.5 W	3.0 W
Power Consumption	35 W	28 W
Subsystem Mass	8.0 kg	25.2 kg
Bit Error Rate (with coding)	10^{-5}	10^{-5}
RCV Antenna	10 m	34 m
Atmos. Transmission Factor	50%	100%
Link Margin	3.6 dB	3.6 dB
Data Rate (with coding)	2 kbps	0.04 kbps

These examples show how the optical communications technology has matured and depicts it's relative advantage over the classical RF technology for long-distance links. Actually, the theoretical advantage of optical (at visible wavelengths) to traditional X-band communications is 71 dB.[11] 1 his advantage is usually used to realize only modest improvements (factors of 10-100) in data rates, as the rest of the advantage is used to reduce telescope apertures or reduce laser powers.

Interstellar Design Example

We now apply the results of the above sections to the design of an optical communications link from a spacecraft at interstellar distances. Table 4 shows the selected design parameters for a link from a spacecraft at a distance of 4 LY. I-he design assumes technology that is either here today, or can reasonably be expected to exist at the earliest time such a mission might happen (say 201 O).

Table 4. Design Parameters for Communications L. Ink at 4 LY Distance

Component Parameters	
Wavelength (pm)	0.532
Average laser output power (W)	20.0
Diameter of XMTR aperture (m)	3.0
Obscuration diameter of XMTR (m)	0.2
1 ransmitter optics efficiency	0.9
XM1 R pointing bias error (µrad)	0.03
XM1 R rms pointing jitter (µrad)	0.03
Diameter of RCVR aperture (m)	10.0
Obscuration diameter of RCVR (m)	2.0
Receiver optics efficiency	0.8
Narrowband filter transmission factor	0.8
Filter spectral bandwidth (angstroms)	0.1
Detector quantum efficiency	0.8
Detector diameter field of view (µrad)	1.2981
Operational Parameters	
PPM alphabet (M = 1 0)	1024
Data rate (kbps)	0.01
Dead time (µsec)	0.99999×10^{6}
Slot width (nsec)	10.0
Distance between XMTR and RCVR (AU)	2,500
Atmospheric transmission factor	1.0
Required link bit error rate	10^{-3}
Noise sources	α Centauri

In this design a frequency-doubled Neodymium YAG (Nd:YAG) laser operating at a wavelength of 0.532 microns is assumed. A power of 20 W has been selected as a reasonable projection for the technology by the year 2010. Presently JPL has developed a laser-diode-pumped, frequency-doubled, Nd:YAG laser that has output 3.5 W of average power in a single spatial mode beam,[12] and power levels are increasing yearly. I-he transmitting aperture is a diffraction-limited 3.0 m diameter telescope. This corresponds to an aperture only slightly larger than the current Hubble Space Telescope. Pointing of the telescope's beam can be accomplished by spatially locking onto the light from our own Sun and using it as a pointing reference. A residual pointing error (bias and jitter, each) of 10% of a beamwidth is reasonable and will result in less than 0.7 dB of link loss.

The receiving aperture is a 10 m diameter telescope. By the time such a mission would reach such a distant target, it is assumed that a 10 m telescope can be easily placed in Earth orbit. (Using a ground-based receiver is also possible with a small penalty in link performance due to atmospheric absorption). Note, however that the telescope detector's field-of-view is 1.3 microradians which corresponds to a blur circle at the focal plane 10 times larger than the diffraction limit. This will help keep the costs of the receiving telescope down.

The operational parameters for the link begin with a PPM signaling alphabet size of 1024 (10-bits). This is a very realistic, and at the same time very efficient, alphabet size. (Note: The original 2.5 bit/photon demonstration performed in 1980 used an alphabet of 256 which corresponds to 8-bits). The data rate is chosen to be 10 bps.

Table 5. Design Control Table for Communications Link at 4 LY Distance

	Factor	dB
Laser output power (W)	20.0	43.0 dBm
Minimum required peak power (W) = 0.20 x 10^{10}		
Transmitter antenna gain	0.252 X 10^{15}	144.0
Antenna diameter (m) = 3.000		
Obscuration diameter (m) = 0.200		
Total beam width (μrad) = 0.289		
transmitter optics efficiency	0.900	-0.5
Transmitter pointing efficiency	0.851	-0.7
Bias error (μrad) = 0.030		
RMS jitter (μrad) = 0.030		
Space loss (250000 AU)	0.128 x 10^{-47}	-478.9
Atmospheric transmission factor	1.00	0.0
Receiver antenna gain	0.335 x 10^{16}	155.2
Antenna diameter (m) = 10.000		
Obscuration diameter (m) = 2.000		
Field of view (μrad) = 1.298		
Receiver optics efficiency	0.800	-1.0
Narrowband filter transmission	0.800	-1.0
Bandwidth (Angstroms) = 0.100		
Received signal power (W)	0.106 x 10^{-16}	-139.8 dBm
Received background power (W) = 0.923 x 10^{-11}		
Detector quantum efficiency	0.8	-1.0
Photons/joule	0.268 x 10^{19}	154.3 dB/mJ
Detected signal PE/second	22.7	13.6 dBHz
Sym[illegible]	1.00	0.0 dB/Hz
Detected signal PE/symbol	22.7	13.6
Required signal PE /second	11.4	10.6
Detected background PE/slot = 0.198		
Margin	2.00	3.0

This might *seem* like a very low data rate, but recall the extreme distances involved and the data playback can occur over years. To provide for much higher data rate would strain the communications system capabilities and would be hard to justify based on the long travel time. The slot width is an engineering parameter and corresponds to the characteristic pulse integration time at the detector. The 10 ns value used here is typical of what is used today. The range is the distance between the spacecraft transmitter and the Earth receiver and corresponds to 4 LY (1/4 million AU). Finally, the link bit error rate specified is 10-3. This might seem extremely high if it told the whole story. However the program used to analyze link performance calculates the channel "Symbol error rate" assuming no channel coding is being used. By employing a rudimentary coding scheme (one which is available today) the resulting coded bit error rate will be well below 10-6.

For background noise, we assume that Alpha Centauri is directly behind the spacecraft transmitter and that the receiving telescope is looking directly at the spacecraft and the star. However, most of the star light is filtered out by the narrow optical bandpass filter whose bandwidth is 0.1 Angstroms. Atomic resonance filters today have gotten down to 0.01 Angstroms with high (8094.) throughput efficiency.

Table 5 shows the resulting Design Control I-able. This table was calculated using the JPL "OPTI" link analysis program developed in the 1980's and validated frequently since. The program is available through the NASA COSMIC software data base.

Looking at the last few lines of the table shows that the number of detected signal photons per transmitted pulse is 22.7 and that the average number of background-generated noise photons in each slot (including the signal slot) is 0.198. The required number of signal photons per pulse to achieve the 10-3 (uncoded) "symbol error rate" is 11.4, which means that the link can be established with a 3.0 dB margin.

The parameter values used in this analysis are achievable based on reasonable projections from today's technology base. The analysis, however, does not make any provisions for significant technology breakthroughs which could certainly make the establishment of such links even more feasible.

Conclusions

This study of a hypothetical mission at 4 LY distance has shown that realistic communications links, using realizable technology and returning modest data rates, can now be envisioned. Although such links could be designed at radio frequencies, they would probably not be economically feasible under the currently prevailing programmatic guidelines. RF-based architectures require very high spacecraft transmitter power levels, with all the resulting implications for flight system mass, and consequently cost. Though RF links may never be appropriate for use on microspacecraft, they may eventually prove useful on larger vehicles and installations. Toward this end, advanced technology developments in RF amplifiers, emphasizing higher frequencies, power levels and efficiencies will be needed. Large spacecraft antenna apertures will also be required, although mass implications of these devices will be mitigated by the rapidly advancing technology of inflatable structures. However, such large spacecraft antenna structures will require greater surface precision to acquire more efficiency at the millimeter wavelength frequencies. Arraying of ground antennas is always an option, though possibly an expensive one. However, there is undoubtedly much room for improvement in the economics of large ground-based antennas. Finally, the state-of-the-art in ground electronics has been advancing rapidly and is expected to continue to do so. Improvements in signal processing techniques and system noise temperature reductions are two key areas which can be expected to contribute to the feasibility of RF links at interstellar distances.

Optical frequencies are much more likely to be used for interstellar communications architectures. Optical communications offers comparable or better link performance, and requires much lighter weight spacecraft equipment, less power, smaller ground systems, and most importantly, less overall expense in order to achieve the same mission objectives. Much progress has been made in the understanding of optical communications techniques since the early interstellar studies were conducted in the 1970s. This has been paralleled by corresponding progress in optical communications systems and hardware, especially in the areas of laser power and efficiency. These developments form the basis of the realistic interstellar links described in this paper. Nonetheless, formidable challenges still remain even at these frequencies, e.g., development of low-cost, lightweight, diffraction-limited transmitting optics in the 3 m class.

Design of viable communication links at light-year distances is, at the least, an interesting intellectual exercise, and eventually a necessary part of an actual interstellar mission design. In the near-ferm it will hopefully prove to be something of more practical value. The engineering challenges that characterize this communications regime may point the way to new technology breakthroughs thaf can be applied directly to near-term problems in space communications, thereby benefitting the field as a whole.

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